Complications After Fasciotomy Revision and Delayed Compartment Release in Combat Patients

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Background: **Incomplete or delayed fasciotomies are associated with muscle necrosis and death in civilian trauma. Combat explosions severely damage tissue and distort normal anatomy making fasciotomies challenging. Rapid air evacuation may delay treatment of patients with evolving extremity compartment syndrome. We investigated the impact of fasciotomy revision and delayed compartment release on combat casualties after air evacuation.**

Methods: **A retrospective review was performed of combat casualties who underwent fasciotomies in Iraq, Afghanistan, or at Landstuhl Regional Medical Center between January 1, 2005 and August 31, 2006. Outcomes were rates of muscle excision, major amputation, and mortality.**

Results: **A total of 336 patients underwent 643 fasciotomies. Most were to the lower leg (49%) and forearm (23%). Patients who underwent a fasciotomy revision had higher rates of muscle excision (35% vs. 9%, $p < 0.01$) and mortality (20% vs. 6%, $p < 0.01$) than those who did not receive a revision. The anterior and deep compartments of the lower leg were the most commonly unopened. Patients who underwent fasciotomy after evacuation had higher rates of muscle excision (25% vs. 11%), amputation (31 vs. 15%), and mortality (19% vs. 5%) than patients who received their fasciotomies in the combat theater ($p < 0.01$). Patients who underwent revisions or delayed fasciotomies had higher Injury Severity Score and larger burns as well as lower systolic blood pressure, acidosis, and more pressor use during air evacuation. These patients also received more blood products at Landstuhl Regional Medical Center.**

Conclusion: **Fasciotomy revision was associated with a fourfold increase in mortality. The most common revision procedures were extension of fascial incisions and opening new compartments. The most commonly unopened compartment was the anterior compartment of the lower leg. Patients who underwent delayed fasciotomies had twice the rate of major amputation and a threefold higher mortality.**

Key Words: **Fasciotomy, Compartment syndrome, Extremity, Revision, Delayed, Combat wounds, OIF, OEF.**

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Most wounds from the conflicts in Afghanistan and Iraq are extremity injuries[1,2] because of fragmentation injury from explosions.[3] Explosions can cause fractures, tissue loss, and vascular injury, all of which place extremities at risk for compartment syndrome. When acute extremity compartment syndrome (ECS) is present, the indication for fasciotomy is clear. Pearse et al. defined acute ECS as "a surgical emergency characterized by raised pressure in an unyielding osteofascial compartment" that can be caused by trauma, revascularization procedures, or exercise.[4] Surgeons must make rapid treatment decisions including when to perform fasciotomy. Specific events that may lead to ECS after injury include hemorrhage from a fracture or arterial injury into an intact compartment, myocyte edema after ischemia-reperfusion injury,[5] or resuscitation.[6] The most common sites of ECS development are the lower leg (53%–62%), followed by forearm (24%–26%), thigh (4%–15%), foot (4%–5%), and hand.[7] In patients with compartment syndrome of the leg, the anterior compartment is involved 62% to 96% of the time, and is the only compartment involved in 29% to 48% of cases.[7] Timing and adequacy of fasciotomy for ECS is a well-described source of morbidity after significant injury.

A clinical diagnosis of compartment syndrome may be made when one or more signs and symptoms are present: pain out of proportion to the injury with or without pain on passive stretch, sensory changes, weakness, or paralysis. Compartment pressures ($\geq$30 mm Hg)[6] or perfusion pressures (diastolic pressure minus compartment pressure $<$30 mm Hg)[8] may be used as diagnostic adjuncts or to monitor at-risk compartments in unconscious or uncooperative patients. Confirmation of compartment syndrome is made in the operating room when fasciotomy is performed and muscle bulges from its compartment.[7] When no compartment syndrome is present, civilian surgeons may forgo primary fasciotomy and opt for serial examinations and compartment pressure monitoring in patients at risk for development of ECS. The Emergency War Surgery Manual[9] discourages this approach in combat-wounded patients since transfers and other factors make continued, close monitoring of patients' symptoms and compartment pressures difficult. Combat surgeons usually transfer stabilized patients to higher levels of care because of personnel and supply limitations at far forward medical facilities. The air evacuation flight from theaters of operation in Afghani-

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stan and Iraq to Landstuhl Regional Medical Center (LRMC) in Germany last from 5 to 9 hours in addition to a minimum of 1 to 2 hours of aircraft loading and unloading and ground transportation. During air evacuation, serial examinations and emergent fasciotomy are extremely difficult to perform. Distracting injuries, analgesics, and sedation may make patients unlikely to report developing ECS symptoms. For these reasons, the decision whether or not to perform fasciotomy before air evacuation is important in combat.

The predominance of extremity injury in the wars in Afghanistan[1] and Iraq,[2] and the possibility of delays in care because of evacuation needs prompted us to investigate fasciotomy outcomes in casualties from the current conflicts. Our objectives were to describe the mechanism and types of injuries associated with limbs undergoing fasciotomy and to compare outcomes between different patient groups. We hypothesized that patients who underwent fasciotomy revision or delayed fasciotomy would have higher rates of muscle excision, limb loss, and death when compared with patients who underwent initial early fasciotomies before transfer out of the combat theater.

METHODS

LRMC in Germany receives all wounded US casualties from combat theaters in Afghanistan and Iraq. The teams at LRMC provide continuing General Surgery, Orthopedic, ENT, OMFS, Ophthalmology, Neurosurgery, and Critical Care services to patients before transfer to the United States. Surgery staff at LRMC maintains a registry of casualties from Operations Enduring and Iraqi Freedom who underwent fasciotomy in theater or at LRMC. A list of service members treated from January 1, 2005 to August 31, 2006 was obtained from this registry. A retrospective review of paper medical charts from these patients was performed. In addition to standard inpatient data from LRMC, the medical records contain an initial history and physical taken on presentation in theater, operation reports from the combat theater, and an air evacuation request completed before transfer to LRMC. Information from the patients' paper charts was used to construct a study database. Demographic data, mechanism and date of injury, percent of total body surface area (% TBSA), associated injuries, anatomic location of fasciotomy, timing, and geographic location of fasciotomy operation were collected. Outcomes data collected were rates of excision of nonviable muscle at LRMC. Injury severity scores (ISSs) were collected from the Joint Theater Trauma Registry database. The Military Amputee Research Program database was used to determine final rates of major amputations among survivors. Mortality data were collected from a search of the publicly accessible Department of Defense Personnel and Procurement Statistics (search performed on performed January 3, 2007).

A diagnosis of acute ECS was considered present when the diagnosis was documented or when one or more signs and symptoms were described in the medical record (pain out of proportion to the injury with or without pain on passive stretch, sensory changes, weakness, or paralysis). Prophylaxis was considered the indication for fasciotomy when physicians cited the mechanism, type of injury, ischemic time, or risk for development of ECS as indication for fasciotomy. Fasciotomy revision procedures included extension of skin and fascial incisions or decompression of a previously unopened compartment. Muscle excision was determined by review of dictated operative note at LRMC and was used as an outcome because muscle loss is likely to translate into loss of function. Other outcomes included rates of major amputation and death.

Patients who underwent fasciotomies in theater were divided into two groups based on whether or not they underwent fasciotomy revision at LRMC. The total study population was also divided into two groups based on whether or not they had undergone a fasciotomy in theater before air evacuation (early) or after transfer to LRMC (delayed). Data are presented as mean $\pm$ SD or percent of patients unless otherwise specified. Outcomes, injury patterns, and treatments were compared using χ^2 for binomial variables or Student's t test for continuous variables. Statistical significance was determined at $p < 0.05$.

RESULTS

Demographics

From January 2005 through August 2006, 2,587 US military personnel serving in Afghanistan or Iraq were admitted to LRMC. Four hundred eight patients underwent fasciotomy in theater or at LRMC during the study time period. Thirty-eight records were not available for review, leaving 370 charts available for review. Of these, 34 were excluded for having no fasciotomy, having a fasciotomy for a noncombat or sports-related wound or being non-US military personnel. The remaining 336 (13% of total Operations Enduring and Iraqi Freedom admissions to LRMC) comprise our study population. Of these, 99% were men, average age 27 $\pm$ 7 years. Two hundred eighty-eight patients (86%) were injured in explosions, 42 (13%) gunshot wounds, 10 (3%) motor vehicle crashes, 1 (0.3%) electrical burns. Most of the explosions (83%) were from improvised explosive devices. The mechanism of injury was penetrating in 77% of patients, blunt in 14%, and burns (>1% TBSA) in 26%. The average total body surface area among the 72 burned patients was 37 $\pm$ 28. Table 1 is a summary of the demographic data. In our population of patients 203 of 336 (60%) had 460 fractures. The most common fractures were tibia, fibula, and foot/ankle. One hundred six patients had specific documentation of the method of in-theater fracture fixation in their medical records. Ninety of 106 (85%) were immobilized with external fixation. Almost one third (108 of 336, 32%) of the patients underwent a vascular ligation or repair. The most common vascular repairs were to the superficial femoral artery followed by popliteal and brachial arteries. The most commonly ligated arteries in patients who underwent fas-

Table 1 Demographics

	No. Patients	Percent
Total	336	
Mean age (yr)	26.5 ± 7.3	
Sex (male/female)	332 (99%)/4 (1%)	
Average ISS	17.1 ± 14.5	
Mode of injury		
Explosion	288	86
Gunshot	42	13
MVC	10	3
Mechanism of injury		
Penetrating	258	77
Blunt	46	14
Burn	89	26
Average %TBSA burn	37.2 ± 27.6	
Inhalational injury	30	9
Abdominal compartment syndrome	13	4
Muscle excision	44	13
Major amputation	55	16
Mortality	26	8

ciotomy were either the ulnar, radial, or profunda femoris arteries.

In-Theater Fasciotomies

In theater, 494 fasciotomies were performed on 294 patients; 65% of patients had at least one sign or symptom of compartment syndrome. The most common types of fasciotomies performed in theater were calf (252) and forearm (110) followed by thigh (41), upper arm (36), hand (28), and foot (24).

Fasciotomy Revisions

Most patients (243 of 294, 83%) who underwent fasciotomies in theater did not undergo revision at LRMC. Only 17% of patients underwent fasciotomy revision. Figure 1 shows the distribution of fasciotomies performed in theater and revision procedures performed at LRMC. A total of 69 revision procedures were performed in 51 patients. Sixty-one percent of the fasciotomies revised were to the lower leg and 25% forearm, 6% hand, 6% arm, 1% thigh, 1% foot, and 1% were undetermined from the records. Fascial incisions were extended in 63% of patients, skin incisions were extended in 14%, and additional compartments were opened in 41%. Of the 37 unopened compartments, 30 were in the lower leg; the most commonly unopened compartments were the anterior (12) and deep posterior compartments (11), followed by the superficial posterior (5) and lateral compartments (2). The other unopened compartments were three carpal tunnels, one forearm flexor compartment, one triceps compartment, and one hypothenar compartment. Of the 51 patients, who underwent fasciotomy revision, 35% underwent muscle excision compared with 9% among patients who did not undergo revision ($p < 0.01$). The rate of major amputation among survivors was not different (24% vs. 16%, NS). The mortality rate among patients who underwent fasciotomy revision was higher in patients who did not undergo revision (20% vs. 6%, $p < 0.01$). These outcomes are summarized in Figure 2.

Further analysis revealed that patients who underwent fasciotomy revision had a higher ISS and larger burns. Patients who underwent fasciotomy revision were more likely to have a burn to the fasciotomized extremity and have undergone an escharotomy. However, they were less likely to have an open wound to the extremity or a fracture. Patients who underwent fasciotomy revision were more likely to have undergone their in-theater fasciotomy on a return trip to the operating room (secondary fasciotomy). Additionally, they were more likely to arrive to LRMC with a lower systolic blood pressure and receiving vasopressors. These results are summarized in Table 2.

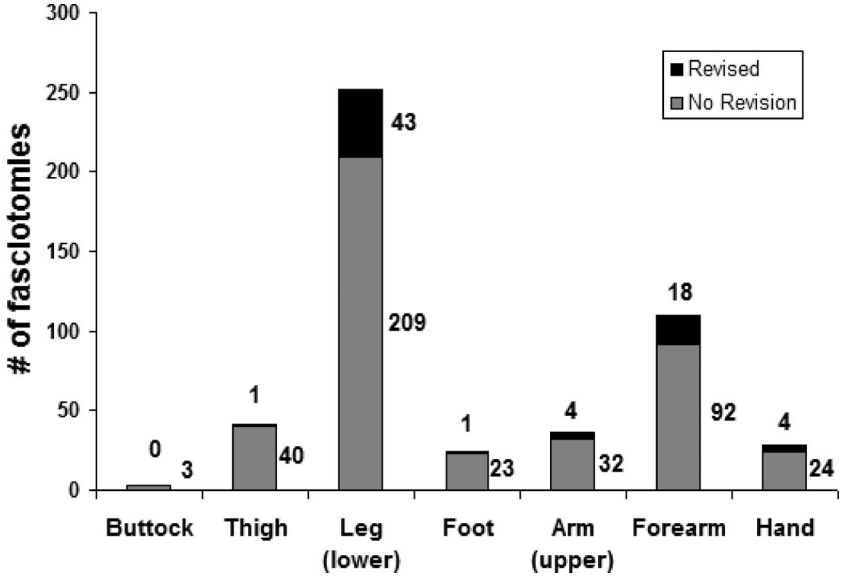

Fig. 1. *Anatomic distribution of fasciotomies performed in theater.*

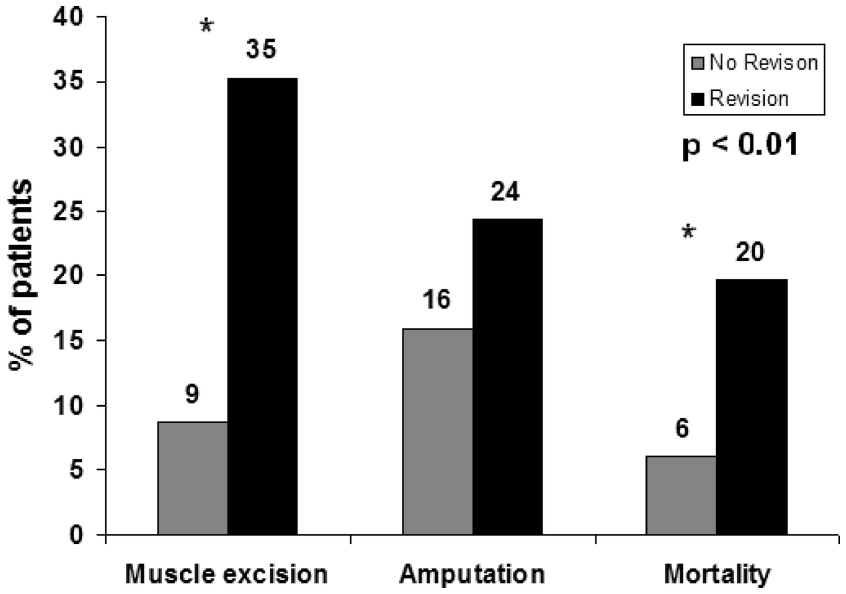

Fig. 2. *Outcomes of patients who underwent in-theater fasciotomies with and without revision.*

Table 2 Comparison of Patient Injuries and Treatments Between Patients Who Underwent In-Theater Fasciotomies With and Without Revision

	No Revision	Revision	n	*p*
Injury severity and burns				
ISS	15.9 ± 13.5	23.5 ± 17.8	301	0.01
Intubated (% of patients)	46	56	154/324	NS
TBSA (%)	32.4 ± 27.3	50.3 ± 24.3	89/336	0.01
Inhalational injury (% of patients)	9.7	17.70	30/336	0.02
Burn to extremity (% of patients)	15.1	39.2	63/336	0.001
Escharotomy in theater (% of patients)	9.5	27.5	41/336	0.001
Open wounds and fractures				
Open wound to extremity (% of patients)	79.3	62.8	258/336	0.01
Fracture (% of patients)	62.8	47.1	203/336	0.05
Pelvic fracture (% of patients)	6.0	5.9	20/336	NS
Gunshot wound (% of patients)	13.7	5.9	42/336	NS
Blunt mechanism (% of patients)	13.7	13.7	46/336	NS
Laparotomy in theater (% of patients)	17.5	25.5	63/336	NS
Abdominal CS in theater (% of patients)	2.8	9.8	13/336	0.02
Extremity CS in theater (% of patients)	55.4	64.7	191/336	NS
Secondary fasciotomy				
Secondary fasciotomy (% of patients)	45.7	67.9	104/214	0.03
Blood pressure and resuscitation				
SBP during air evacuation (mm Hg)	122 ± 22	112 ± 21	211	0.001
DBP during air evacuation (mm Hg)	64 ± 14	64 ± 13	211	NS
SBP on arrival to LRMC (mm Hg)	126 ± 22	118 ± 22	325	0.0002
DBP on arrival to LRMC (mm Hg)	68 ± 14	64 ± 15	322	0.001
Pressors during air evac (% of patients)	18.3	55.3	56/229	0.0001
HCO_3	25.5 ± 3.3	24.6 ± 4.2	275	0.03
Lactate (mmol/L)	1.9 ± 1.1	2.6 ± 1.6	163	NS
Base deficit	3.1 ± 3.9	3.7 ± 4.2	142	NS
PRBC at LRMC (units)	2.0 ± 3.2	3.6 ± 4.5	307	0.003
FFP at LRMC (units)	1.2 ± 3.3	2.1 ± 4.0	200	0.03
Outcomes (%)				
Muscle excision	9	35	44/305	0.001
Amputation	16	24	55/310	NS
Mortality	6	20	26/336	0.01

CS indicates compartment syndrome; PRBC, packed red blood cells; FFP, fresh frozen plasma.

LRMC Fasciotomies

During our study time period, 73 patients underwent 177 fasciotomies at LRMC. Most (85%) patients had a diagnosis of compartment syndrome at the time of fasciotomy. The most common fasciotomies performed at LRMC were calf (63), forearm (39), thigh (34), and upper arm (28). Figure 3 summarizes the distribution of fasciotomies in theater and at LRMC. Patients who underwent fasciotomy after evacuation (delayed) had higher rates of muscle excision (25% vs. 11%, $p < 0.01$), amputation (31 vs. 15%, $p < 0.01$), and mortality (19% vs. 5%, $p < 0.01$) than patients who received their fasciotomies in theater (early). Figure 4 summarizes these outcomes.

We determined that patients who underwent early versus delayed fasciotomies had a lower ISS and were less likely to have burns or inhalational injury. Patients who underwent early fasciotomies were more likely to have an open wound to the extremity that underwent fasciotomy. However, patients who underwent delayed fasciotomies were more likely to have other major traumatic injuries (laparotomy, pelvic fracture) and blunt injuries. Patients in the delayed fasciotomy group also had lower mean blood pressures during air evacuation and on arrival to LRMC. They were more likely to be acidotic and receiving vasoactive medications. Additionally, the delayed group required more blood products during their hospital course at LRMC. These results are summarized in Table 3.

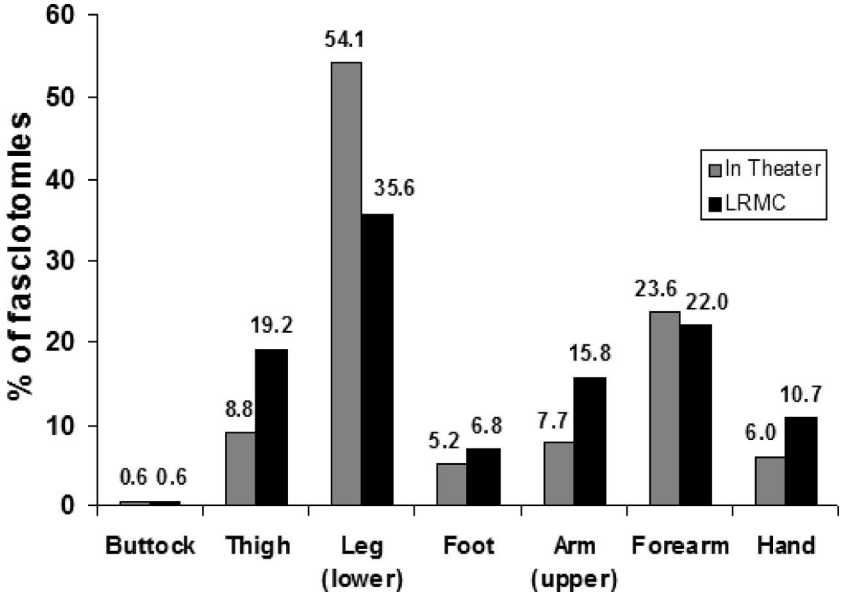

Fig. 3. *Distribution of fasciotomies by anatomic and geographic location.*

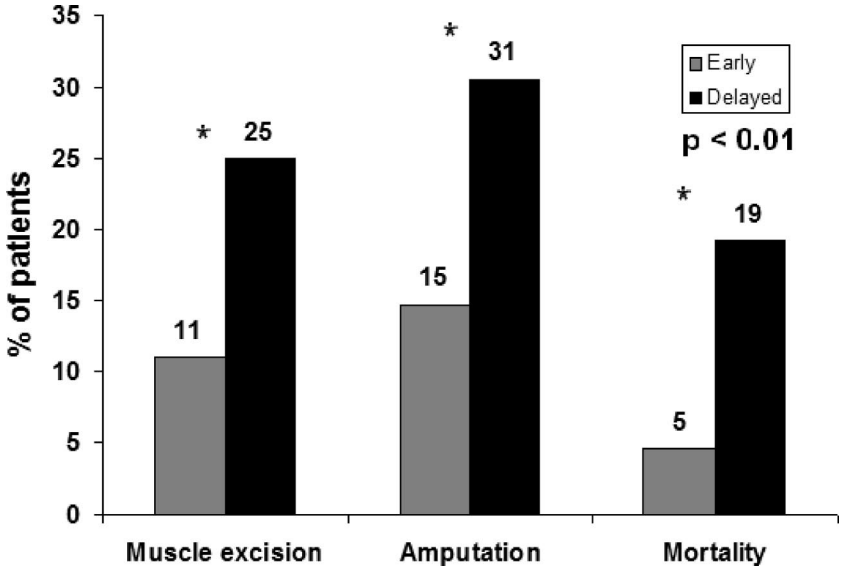

Fig. 4. *Outcomes of patients who underwent early (in-theater) fasciotomies compared with those whose fasciotomies were delayed until after transfer to LRMC.*

Table 3 Comparison of Patient Injuries and Treatments Between Patients Who Underwent Early or Delayed Fasciotomies

	Early	Delayed	n	*p*
Injury severity and burns				
ISS	14.5 ± 12.9	26.2 ± 16.2	301	0.0001
Intubated (% patients)	38.4	72.6	154/324	0.001
TBSA (%)	29.6 ± 27.8	48.4 ± 23.4	89/336	0.01
Inhalational injury (% of patients)	4.6	24.7	30/336	0.001
Burn to extremity (% of patients)	13.7	37.0	63/336	0.001
Escharotomy in theater (% of patients)	6.1	34.3	41/336	0.001
Injuries and in-theater diagnoses				
Open wound to extremity (% of patients)	82.9	54.8	258/336	0.001
Fracture (% of patients)	62.4	53.4	203/336	0.01
Pelvic fracture (% of patients)	3.0	16.4	20/336	0.001
Gunshot wound (% of patients)	14.5	5.5	42/336	0.05
Blunt mechanism (% of patients)	10.3	26.0	46/336	0.001
Laparotomy in theater (% of patients)	28.4	45.5	63/336	0.03
Abdominal CS in theater (% of patients)	1.2	13.7	13/336	0.001
Extremity CS in theater (% of patients)	65.4	26.0	191/336	0.001
Time from injury to fasciotomy				
Time from injury to fasciotomy (h)	5.6 ± 5.6	26.2 ± 22.0	115	0.0001
Blood pressure and resuscitation				
SBP during air evacuation (mm Hg)	123 ± 21	113 ± 23	211	0.05
DBP during air evacuation (mm Hg)	65 ± 14	60 ± 13	211	0.02
SBP on arrival to LRMC (mm Hg)	128 ± 20	115 ± 24	325	0.0001
DBP on arrival to LRMC (mm Hg)	69 ± 14	63 ± 15	322	0.01
Pressors during air evac (% of patients)	16.6	50.0	56/229	0.001
HCO_3	25.9 ± 3.1	23.7 ± 4.1	278	0.001
Lactate (mmol/L)	1.7 ± 1.0	2.6 ± 1.6	163	0.001
Base deficit	2.5 ± 3.4	4.3 ± 4.6	142	0.05
PRBC at LRMC	1.6 ± 2.5	4.4 ± 5.1	307	0.0001
FFP at LRMC	0.8 ± 2.8	3.3 ± 4.4	200	0.001
PLT at LRMC	1.2 ± 3.8	5.6 ± 8.6	193	0.01
Outcomes (%)				
Muscle excision	11	25	44/336	0.001
Amputation	15	31	55/310	0.01
Mortality	6	20	26/336	0.001

DISCUSSION

Our retrospective review of 336 patients and 671 combat fasciotomies demonstrates a similar anatomic distribution to previous civilian studies. The most common fasciotomies performed in civilian trauma centers and in our series were calf, followed by forearm, then thigh. Calf and forearm fasciotomies alone accounted for 78% of fasciotomies performed in theater. Previous studies have demonstrated an association between injuries such as fracture,[10] vascular trauma,[5] and burns[11] and need for fasciotomy. In our series of patients who underwent fasciotomies, 60% had fractures, 32% had vascular injury, and 26% had burns.

In previous studies, the indications for prophylactic fasciotomy and predictors of ECS have been difficult to determine.[12] However, certain injury patterns have been associated with higher likelihood of fasciotomy. ECS can be associated with orthopedic or vascular injuries. Blick et al. found a close association between grade of fracture, degree of comminution, and risk of development of ECS in a retrospective review of 198 open tibia fractures.[10] Abouezzi et al. found a 28% incidence of fasciotomy in patients with peripheral vascular injuries treated at a Level I trauma center. They determined that injury to popliteal vessels was more likely (62% cases) to result in fasciotomy than above the knee vascular injury (19% cases).[5] Another study evaluated femoral vascular injuries in particular and found that the rates of fasciotomy depended on whether there was isolated arterial (13% fasciotomy) or venous injury (3% fasciotomy), or a combination (38% fasciotomy).[13] Massive edema from burns combined with high-volume fluid resuscitation places all extremities in severely burned patients at risk for compartment syndrome.[11] The risk of ischemia-reperfusion injury should also make warm ischemia time >6 hours a consideration in determining need for fasciotomy.[5]

Even when these risk factors are recognized, errors in surgical technique may contribute to poor outcomes. Guerrero et al. found an 8% incidence of ECS in patients who underwent primary prophylactic fasciotomy at the time of ligation or repair of lower extremity arterial injury. Interestingly, the investigators found no statistically significant difference in the incidence of ECS in patients who underwent prophylactic fasciotomy when compared with those who did

not. The authors attributed the occurrence of ECS despite fasciotomy to the "limited" nature of the fasciotomies and observed that this occurred mostly in patients with popliteal artery injury. They noted a 41% amputation rate in patients who developed postoperative ECS, which was significantly higher than the 6.7% amputation rate in those who did not.[12] Another study found that even with adequate fascial incisions, inadequate skin incisions prevented complete compartmental decompression.[14]

Previous civilian studies have calculated that need for revision of fasciotomies or escharotomies occurs in 8% to 44% of patients.[11,12] In our study, 16% (53 of 336) of patients underwent fasciotomy revision. It is noteworthy that this is at the lower end of the spectrum described in civilian literature. Our patients who underwent revision had higher rates of muscle excision and death than patients who underwent adequate initial fasciotomies. These data suggest that extensive fasciotomies may be needed to minimize muscle excision and optimize limb function and survival. Extending incisions beyond what is needed for compartment release at the time of initial surgery may be advisable to allow progression of muscle edema without hemodynamically significant increase in compartment pressure.

The most commonly unopened compartments were the anterior and deep compartments of the lower leg. The anterior compartment is of particular importance because it is involved in most cases of lower ECS and can be the only compartment affected in up to half of all cases.[7] Identification of anatomic landmarks may be quite difficult in the mangled extremity, therefore, training should highlight the importance of using tactile methods to confirm compartment release. Simple techniques may help, such as touching the lateral aspect of the tibia to demonstrate entrance into the anterior compartment and touching the medial aspect of the fibula to prove release of the deep posterior compartment.

Fasciotomy in a combat environment or in any situation where a long transfer is anticipated should entail complete release of skin and fascia of all compartments in the extremity undergoing decompression. The most commonly revised fasciotomies were to the calf and forearm. The most frequent revision procedures were extension of fascial incisions and decompression of unopened compartments. Predeployment training efforts should focus on when to perform fasciotomy and prioritize proper surgical technique for fasciotomies of calf and forearm. Emphasis should be placed on opening all compartments with incisions of adequate length in an effort to prevent the need for fasciotomy revision and, possibly, improve outcomes.

In addition to surgical technique, timing of fasciotomy is critical because after 8 hours of total ischemia irreversible damage has been done to muscle and peripheral nerve.[15] The rate of delayed fasciotomy in the civilian trauma literature ranges from 7% to 30% and has been associated with increased rates of muscle necrosis, amputation, and mortality.[11,16–18] Hope and McQueen found that a 12.4-hour greater mean delay to fasciotomy increased rates of muscle necrosis from 8% of patients to 20%.[7] Sheridan and Matsen reported that when fasciotomy was performed more than 12 hours after onset of weakness, hypesthesia or pain on passive stretch, normal limb function was restored in only 8% of patients. Almost half of the patients in their series who underwent delayed fasciotomy ultimately required amputation.[19] Finkelstein et al. reviewed the cases of five patients who underwent delayed fasciotomy (average ischemic time 56 hours) for ECS after closed injury to the lower extremity. Three of five patients developed sepsis, and one died of sepsis and multisystem organ failure. One surviving patient developed renal failure and all surviving patients required amputations. This experience lead the authors to conclude that fasciotomies in patients with ECS diagnosed after 8 hours were consistently associated with severe infection and possible death.[18]

The rate of delayed fasciotomy in our series (22%) was within the range of 7% to 30% reported in the trauma literature.[11,16–18] Previous studies have demonstrated an increased rate of muscle necrosis associated with delayed fasciotomy.[7] Similarly, our data demonstrate that patients who underwent a fasciotomy at LRMC had higher rates of muscle excision, amputation, and death than patients who only received fasciotomies in theater. Our rate of muscle excision (23%) in patients who underwent delayed fasciotomies was similar to the 20% reported by Sheridan and Matsen, but our amputation rate (31%) was lower.[19] The fact that fasciotomy was not performed in theater in these patients indicates that compartment syndrome was either not diagnosed or not present at the time the casualty entered the evacuation system.

Patients who had delayed fasciotomies had more severe, diffuse injuries, and were more likely to have larger burns and pelvic fractures. They were also more likely to arrive on pressors and require a larger resuscitation with packed red blood cells and fresh frozen plasma at LRMC. Additionally, patients with delayed ECS had a higher rate of abdominal compartment syndrome in theater. These facts lend credence to the possibility that this group of patients had received a large volume of fluid resuscitation in theater, had manifested complications, and had continued to require ongoing resuscitation. These data are consistent with the trauma literature that states that patients with a need for large volume resuscitation are at increased risk for delayed ECS.[6]

Other possible explanations for delayed compartment syndrome in our patients abound, including effects of primary blast injury and air evacuation. In our study, 86% of patients were injured in explosions. This mode of injury was not common in civilian studies and may have impacted the progression of edema in our patients. At least one study of the physiologic response to blast injuries has demonstrated that the blast wave can induce a generalized release of inflammatory mediators.[20] Severe or prolonged diffuse capillary leak can increase third-space fluid loss and extremity edema leading to delayed compartment syndrome. This has been described as

Table 4 Comparison of Patients Who Underwent Early Fasciotomies and No Revisions to Patients Who Underwent Revision or Delayed Fasciotomy

	Early	Delayed	n	*p*
Injury severity and burns				
ISS	14.5 ± 12.9	26.4 ± 16.2	301	0.0001
Intubated (% patients)	39.9	74.7	154/324	0.0001
TBSA (%)	29.6 ± 27.8	48.4 ± 23.4	89/336	0.002
Inhalational injury (% of patients)	4.6	25.0	30/336	0.0001
Burn to extremity (% of patients)	13.6	37.5	63/336	0.0002
Escharotomy in theater (% of patients)	6.1	34.7	41/336	0.0001
Injuries and in-theater diagnoses				
Open wound to extremity (% of patients)	82.6	55.6	258/336	0.0001
Pelvic fracture (% of patients)	3.0	16.7	20/336	0.0001
Gunshot wound (% of patients)	14.4	5.6	42/336	0.04
Blunt mechanism (% of patients)	10.2	26.4	46/336	0.01
Laparotomy in theater (% of patients)	14.4	34.7	63/336	0.001
Abdominal CS in theater (% of patients)	1.1	13.9	13/336	0.003
Extremity CS in theater (% of patients)	65.5	25.0	191/336	0.0001
Time from injury to fasciotomy				
Time from injury to fasciotomy (h)	5.6 ± 5.6	26.2 ± 22.0	115	0.0001
Blood pressure and resuscitation				
SBP during air evacuation (mm Hg)	123 ± 21	112 ± 23	211	0.01
DBP during air evacuation (mm Hg)	65 ± 14	60 ± 13	211	0.02
SBP on arrival to LRMC (mm Hg)	128 ± 20	115 ± 24	325	0.0001
DBP on arrival to LRMC (mm Hg)	69 ± 14	63 ± 15	322	0.01
Pressors during air evac (% of patients)	16.6	50.0	57/229	0.004
HCO_3	25.9 ± 3.1	23.7 ± 4.2	275	0.0002
Lactate (mmol/L)	1.8 ± 1.0	2.6 ± 1.6	163	0.002
Base deficit	2.5 ± 3.4	4.3 ± 4.6	142	0.02
PRBC at LRMC (units)	1.6 ± 2.5	4.4 ± 5.2	307	0.0001
FFP at LRMC (units)	0.8 ± 2.8	3.3 ± 4.4	200	0.005
PLT at LRMC (packs)	1.2 ± 3.8	5.6 ± 8.6	193	0.004
Outcomes (%)				
Muscle excision	10	24	44/336	0.01
Amputation	16	33	55/310	0.05
Mortality	5	19	26/336	0.003

secondary ECS. It occurs in uninjured extremities in patients with generalized edema after resuscitation for acute injuries or sepsis. Tremblay et al. found that this phenomenon was rare (10 of 11,996 or 0.08% of trauma admissions).[6] We did not observe development of compartment syndrome in uninjured extremities in our series, however it has been rarely observed at LRMC.

Many factors during air evacuation could possibly increase the likelihood of ischemic muscle progressing to frank necrosis. Hypoxia, hypotension, anemia, and pressor use could decrease perfusion and oxygenation of skeletal muscle and cause necrosis of compromised myocytes. In our opinion, it is more likely that excessive crystalloid resuscitation or dependent limb position in flight exacerbated muscle edema resulting in need for lengthening of fascial incisions and delayed compartment release. Because our rate of delayed compartment syndrome was within the range quoted in civilian trauma literature, it is unlikely that a military-specific injury or altitude-related mechanism is the cause.

One major limitation of this study is that we do not have the volumes of crystalloid and colloid resuscitation during air evacuation. Certainly, patients with lower blood pressure, acidosis, and need for pressors would seem to be more likely to receive aggressive fluid resuscitation in flight. Future studies should investigate the relationship between volume and type of fluid resuscitation during air evacuation and rates of revision and delayed compartment syndrome.

Table 4 combines revision and delay to summarize the differences in characteristics and outcomes in patients who underwent early, in-theater fasciotomies compared with those who had fasciotomy revision or fasciotomies at LRMC. Patients who underwent fasciotomy revision or delayed fasciotomies were more likely to have burns. Tables 2 and 3 show that burned patients were more likely to have both revisions and delayed fasciotomies. This fact highlights the need for increased vigilance for compartment syndrome in our population of patients with combat burns. Clinicians should carefully weigh the risks and benefits of early fasciotomy versus escharotomy alone in patients with circumferential burns and the need for continuing resuscitation. Additionally, higher ISSs, blunt mechanism, in-theater laparotomy, and hypotension during and immediately after air evacuation were associated with revision and delayed fasciotomies. Subgroup analysis demonstrated that of the 15 patients who underwent both fasciotomy revision and delayed fasciotomy (to a different extremity),

60% underwent muscle excision, 47% died, and 50% of the survivors required a major amputation. Perhaps through increased vigilance for compartment syndrome in these severely injured patients, outcomes can be improved. An All Army Activity Memorandum has recently been published summarizing the findings of this study and urging the early use of complete fasciotomies and prophylactic fasciotomies in high-risk patients.

CONCLUSION

Fasciotomy revision was associated with increased rates of muscle excision and mortality among combat casualties. Specifically, fasciotomy revision was associated with a threefold increase in mortality. The most common revision procedures were extension of fascial incisions and opening a new compartment. The most commonly unopened compartment was the anterior compartment of the lower leg. Patients who underwent delayed fasciotomies had twice the rate of major amputation and a fourfold higher mortality when compared with patients who underwent early fasciotomies. Physicians should maintain a high clinical suspicion for delayed compartment syndrome in patients with severe diffuse injuries, large burns, and large volume or prolonged resuscitation.

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REFERENCES

1. Bilski TR, Baker BC, Grove JR, et al. Battlefield casualties treated at Camp Rhino, Afghanistan: lessons learned. *J Trauma.* 2003; 54:814–822.
2. Montgomery SP, Swiecki CW, Shriver CD. The evaluation of casualties from Operation Iraqi Freedome on return to the continental United States from March to June 2003. *J Am Coll Surg.* 2005;201:7–12.
3. Gondusky JS, Reiter MP. Protecting military convoys in Iraq: an examination of battle injuries sustained by a mechanized battalion during Operation Iraqi Freedom II. *Mil Med.* 2005;170:546–549.
4. Pearse MF, Harry L, Nanchahal J. Acute compartment syndrome of the leg. *BMJ.* 2002;325:557–558.
5. Abouezzi Z, Nassoura Z, Ivatury RR, Porter JM, Stahl WM. A critical reappraisal of indications for fasciotomy after extremity vascular trauma. *Arch Surg.* 1998;133:547–551.
6. Tremblay LN, Feliciano DV, Rozycki GS. Secondary extremity compartment syndrome. *J Trauma.* 2002;53:833–837.
7. Hope MJ, McQueen MM. Acute compartment syndrome in the absence of fracture. *J Orthop Trauma.* 2004;18:220–224.
8. Whitesides TE Jr, Haney TC, Morimoto K, et al. Tissue pressure measurements as a determinant of the need of fasciotomy. *Clin Orthop.* 1975;113:43–51.
9. Emergency War Surgery 2004. Available at http://www.brooksidepress.org/products/emergency_war_surgery_entrance.htm. Accessed October 29, 2007.
10. Blick SS, Brumback RJ, Poka A, Burgess AR, Ebraheim NA. Compartment syndrome in open tibia fractures. *J Bone Joint Surg Am.* 1986;68:1348–1353.
11. Brown RL, Greenhalgh DG, Kagan RJ, Warden GD. The adequacy of limb escharotomies-fasciotomies after referral to a major burn center. *J Trauma.* 1994;37:916–920.
12. Guerrero A, Gibson K, Kralovich KA, et al. Limb loss following lower extremity arterial trauma: what can be done proactively? *Injury.* 2002;33:765–769.
13. Cargile JS, Hurt JL, Purdue GF. Acute trauma of the femoral artery, vein. *J Trauma.* 1992;32:364–371.
14. Cohen MS, Garfin SR, Hargens AR, Mubarak SJ. Acute compartment syndrome: effect of dermotomy on fascial decompression in the leg. *J Bone Joint Surg Br.* 1991;73:287–290.
15. Whitesides TE, Heckman MM. Acute compartment syndrome; update on diagnosis an treatment. *J Am Acad Orthop Surg.* 1996;4:209–218.
16. Dente CJ, Feliciano DV, Rozycki GS, et al. A review of upper extremity fasciotomies in a level I trauma center. *Am Surg.* 2004; 70:1088–1093.
17. Williams AB, Luchette FA, Papconstantinou HT, et al. The effect of early vs. late fasciotomy in the management of extremity trauma. *Surgery.* 1997;122:861–866.
18. Finkelstein JA, Hunter GA, Hu RW. Lower limb compartment syndrome: course after delayed fasciotomy. *J Trauma.* 1996;40:342–344.
19. Sheridan GW, Matsen FA. Fasciotomy in the treatment of the acute compartment syndrome. *J Bone Joint Surg Am.* 1976;58:112.
20. Cernak I, Savic Jovan, Ignjatovic D, Jevtic M. Blast injury from explosive munitions. *J Trauma.* 1999;47:96–103.

DISCUSSION

Dr. Mark Bagg (Brooke Army Medical Center, Fort Sam Houston, TX): I would like to congratulate the author and coauthors on a very thorough analysis of 336 patients receiving 643 fasciotomies for combat injuries. Their conclusions appropriately emphasize the importance of early and complete fasciotomy in retaining limb function, limb survival, and patient survival.

The authors evaluated outcomes resulting from two separate groups of patients, those who required revision of a fasciotomy previously performed in theater and those who were treated with delayed fasciotomy at LRMC. Outcomes for each group were then compared with those who received appropriate early fasciotomy.

Fifteen percent (53 of 349 patients) required fasciotomy revision, which is at the low end of the spectrum in the civilian literature. Those who underwent revision had higher rates of muscle excision and death than patients who underwent adequate initial fasciotomy. The most common unopened compartments were anterior and deep posterior compartments of the lower leg and this finding mirrors my own observations. We have always taught that when fasciotomies of the leg are performed, selective fasciotomies should be discouraged and that all four compartments should be released. When releasing the four compartments in a mangled extremity it is very important to adhere to common landmarks to ensure the adequacy of the release, specifically touching the lateral shaft of the tibia to ensure that the anterior compartment is released. This is clearly a surgeon-specific issue that ought to be improved with the specific predeployment training that is now being conducted. Although the delayed fasciotomy patient population is a difficult clinical challenge, the performance of complete and adequate fasciotomy on those patients with clear indications is a matter of fundamental surgical education. Further studies should be undertaken to evaluate

the outcomes of this training to ensure that proper fasciotomy techniques of complete fascial and adequate skin incisions are being adhered to. As a final comment on this group, isolated compartment fasciotomy in the leg is irrational and should not be performed in the combat setting.

A real challenge is exposed in the data and discussion on delayed fasciotomy. In this series, 22% of the fasciotomies were performed at Landstuhl as opposed to in-theater and were classified as "delayed". As in previous published series, those patients had higher rates of muscle excision, amputation, and death.

It is not clear from the data whether the compartment syndrome was not diagnosed in theater or whether the compartment syndrome evolved during the evacuation process. I was very glad to see that the term "missed" compartment syndrome was not used to describe this group of patients. This patient population had generally higher severity of injuries, specifically burns, pelvic trauma, and abdominal compartment syndromes all of whom received large volumes of fluid resuscitation and ongoing resuscitation during evacuation. In addition, as clearly stated by the authors, the unknown effects of blast overpressure on tissue swelling particularly when commingled with high altitude evacuation and immobility in the presence of continued release of inflammatory mediators may be important factors that should prompt further research. The presentation of a patient with a prolonged compartment syndrome has always been a diagnostic and therapeutic dilemma. First, it is hard to know exactly how long decreased perfusion has been present as a compartment syndrome evolves over time. Will releasing a compartment that most likely has dead muscle improve the outcome or just expose dead muscle to the environment? When the compartment syndrome has existed more than 12 hours, actual release of the compartment is fraught with problems with high amputation rates, infection, and even death as documented by other authors. Although this is a study that looks specifically at outcomes of those who have undergone fasciotomies, have the authors considered a case-control study of this group of patients who received delayed fasciotomy to another group who were diagnosed as having had a prolonged compartment syndrome where fasciotomy was not performed to help answer the question on whether delayed fasciotomy actually improves outcome?

Would they consider a case-control study in matching patients for injury distribution and severity who did not require a fasciotomy at Landstuhl in an attempt to develop criteria for minimizing or reducing the incidence and consequences of fasciotomy delay?

What steps have been taken to ensure that surgeons are clearly able to perform adequate and complete fasciotomies? And finally, have the authors formed any impression about the importance of blast injuries in creating anatomic or local physiologic environments, which would seem to prejudice limb survival, healing, and the development of compartment syndrome.

Dr. Amber E. Ritenour (US Army Institute of Surgical Research, Fort Sam Houston, TX): Dr. Bagg, thank you very much for your insightful comments. The issue of fasciotomy revision is a problem that is being addressed by formal predeployment training. The War Extremity Course provides deploying physicians with the opportunity to practice proper fasciotomy technique on cadavers. Of course, anatomic landmarks can be difficult to identify in the badly injured extremity. An interactive training CD is being developed to address the challenges of performing a fasciotomy on an explosion-injured extremity. After implementation of this training a subsequent study will be performed to evaluate its effect of incidence of fasciotomy revision and outcomes.

In the delayed fasciotomy group, it was unclear from the medical record at what point after injury the compartment syndrome began. Tremblay et al. described a secondary extremity compartment syndrome in uninjured extremities after large volume resuscitation.[1] We did not observe compartment syndrome in uninjured extremities in our series. The same mechanisms (capillary leak, hemorrhage, etc.) that cause delayed compartment syndrome in the civilian trauma patient are the most likely cause of compartment syndrome in military wounded as well. Our incidence of delayed compartment syndrome is within the range described in previous civilian studies. Therefore, although studying the local environment of a blast-injured extremity would be interesting, no new military-unique mechanism is necessary to explain our findings.

Some surgeons have questioned the practice of performing delayed fasciotomies because of increased morbidity in the face of little to no functional benefit.[2,3] In our patients, the records available indicate that when symptoms of compartment syndrome were present in theater, fasciotomies were performed. When patients arrive to LRMC after air evacuation, it is difficult, if not impossible, to determine how long a compartment syndrome has been present, leading surgeon's to err on the side of performing a fasciotomy. For these reasons, it is difficult to apply the findings of civilian studies of delayed fasciotomy to our patients.

Finally, a case-control study of patients with similar injury distribution and severity who did and did not undergo fasciotomies at LRMC would be very helpful. This would allow us to determine risk factors for delayed compartment syndrome, which may lead to earlier identification and closer monitoring of selected at-risk patients. Determination of specific risk factors would also allow us to make more detailed recommendations for the treatment of this patient subpopulation, and possibly improve outcomes.

REFERENCES

1. Tremblay LN, Feliciano DV, Rozycki GS. Secondary extremity compartment syndrome. *J Trauma.* 2002;53:833–837.
2. Finkelstein JA, Hunter GA, Hu RW. Lower limb compartment syndrome: course after delayed fasciotomy. *J Trauma.* 1996;40:342–344.
3. Williams AB, Luchette FA, Papconstantinou HT, et al. The effect of early vs. late fasciotomy in the management of extremity trauma. *Surgery.* 1997;122:861–866.